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(57) Abstract

A laser device incorporates a rectangular multi-mode beamsplitter waveguide (20) connected at one end to a retro-reflecting mirror (26). The beamsplitter wave-guide (20) is connected at a second end to an output coupling waveguide (22) and a reflection coupling wave-guide (24). The reflection coupling waveguide (24) is terminated by a second retro-reflecting mirror (27). Ra-diation produced within the device is reflected by the mirror (26) and coupled to the two coupling waveguides in a manner such that a partially reflecting mirror is not required at an output to the device.

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LASER DEVICE

This invention relates to a laser device.

5 Lasers are well known in the prior art, having been first invented in
1960 by T.H.Maiman. In a laser, electromagnetic radiation is reflected
between two ends of a resonating cavity stimulating transitions from
excited energy levels to lower energy levels, which results in the
generation of further photons in phase and travelling in the same
10 direction as the stimulating radiation. The ends of the cavity must be
sufficiently reflecting so that the amount of radiation absorbed or
transmitted at the mirror is less than or equal to the amount of
radiation generated by this stimulation process.   Prior art lasers
include a partially reflecting cavity mirror in their construction to
15 reflect a high percentage of incident radiation back into the cavity and
transmit a small fraction as the laser beam.   Partially reflecting
mirrors incorporating a number of dielectric layers are relatively
expensive to produce; also, partially reflecting mirrors are susceptible
to damage in high power applications.

20

An example of a laser device is a He:Ne gas filled laser as described on
page 486 of the book 'Optics' by E.Hecht and A.Zajac published by the
Addison-Wesley Publishing Company Inc of Massachusetts USA in 1974.

25 The present invention provides a laser device including waveguiding means
and first and second reflecting means arranged to define a resonant
cavity, characterised in that the waveguiding means is arranged to define
radiation intensity maxima at the first reflecting means, an intensity
maximum at least transiently at the second reflecting means, and an
30 intensity maximum at least transiently at an output separate from the
first and second reflecting means.

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The invention provides the advantage that a partially reflecting output mirror is not required, such mirrors being sensitive to power damage. This is the case particularly for high power carbon dioxide lasers.

5 The use of a multi-mode propagating waveguide configured as a laser is described in Patent Cooperation Treaty application number WO 92/11550. This describes a laser incorporating a partially reflecting mirror. Patent Cooperation Treaty patent application number WO 92/11554 describes the use of a multi-mode waveguide as an intensity dividing device.

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The laser device of the invention has a multi-mode beamsplitter waveguide which at a first end is connected to two coupling waveguides, one of which is a reflection coupling waveguide and one of which is an output coupling waveguide. The reflection coupling waveguide is terminated by a
15 fully reflecting mirror. Reflecting means are arranged at a second end of the beamsplitter waveguide.

The device may be arranged so that approximately 85% of radiation coupled to the coupling waveguides is coupled to the reflection coupling
20 waveguide and the remaining 15% is coupled to the output coupling waveguide.

The reflecting means at the second end of the beamsplitter waveguide may include modulation waveguides. The modulation waveguides may be arranged
25 to provide phase control of radiation reflected by the reflecting means. Electro-optic phase modulators may be arranged within the modulation waveguides. These phase modulators may be arranged to correct for changes in the dimensions of the device due to thermal effects; they may also be arranged to operate the device in a Q-switched mode by switching
30 radiation intensity maxima between the coupling waveguides. Operation as a Q-switched laser device gives the advantage that a high intensity pulsed output may be produced. The intensity of the output of the laser device may be controlled by controlling the phase modulators.

The reflecting means at the second end of the beamsplitter waveguide may be a flat mirror, and the radiation intensity maxima coupled to the two coupling waveguides may be of equal intensity.

5

The laser device may be a gas laser with hollow waveguides. The gas provides a gain medium with energy coupled into the gain medium by RF electrodes. Alternatively the laser device may be formed of ridge waveguides of a semiconductor material system which acts as a gain
10 medium. The medium may be excited by a current flowing through the device.

The laser device may have an output coupling waveguide at both ends of the beamsplitter waveguide. Radiation output beams emitted by these
15 output coupling waveguides may be of equal intensity with a constant phase relationship between the output beams.

In order that the invention might be more fully understood, embodiments thereof will now be described, by way of example only, with reference to
20 the accompanying drawings, in which:-

Figure 1 is a horizontal sectional plan view of a laser device of the invention;

25 Figures 2 and 3 are vertical sections along lines II-II and III-III respectively of Figure 1;

Figure 4 shows a family of graphs illustrating electric field intensity distribution along a multi-mode waveguide of identical cross-section to a
30 multi-mode waveguide of Figure 1;

Figure 5 illustrates a laser device of the invention incorporating a sealed cavity;

Figure 6 is a sectional view of a laser device of the invention incorporating controllable phase modulator waveguides;

5 Figure 7 is a schematic view of a laser device of the invention formed of ridge waveguides;

Figures 8 and 9 are vertical sections along lines VIII-VIII and IX-IX respectively in Figure 7;

10

Figure 10 is a horizontal sectional plan view of a laser device of the invention arranged to couple laser radiation intensity equally between two coupling waveguides;

15 Figure 11 is a horizontal sectional plan view of a laser device of the invention arranged for Q-switched operation;

Figure 12 is a horizontal sectional plan view of a laser device of the invention incorporating two output coupling waveguides.

20

Referring to Figures 1, 2 and 3, there are shown sectional views of a laser device of the invention indicated generally by 10. Figure 1 is a horizontal sectional view of the laser device 10. Vertical sections on lines II-II and III-III in Figure 1 are shown in Figures 2 and 3 25 respectively.

The laser device 10 incorporates two sheets of alumina, these being a base sheet 12 and a cover sheet 14. The sheets 12 and 14 are plane surfaced and parallel to one another. The position of the interface 30 between the cover sheet 14 and the base sheet 12 is indicated by dashed lines 16 in Figures 2 and 3.

The base sheet 12 is formed from a solid piece of alumina by milling to produce a beamsplitter waveguide 20 with an output coupling waveguide 22 and a reflection coupling waveguide 24. The waveguides 20, 22, and 24 have side walls and lower walls (not shown) defined by flat surfaces
5 formed by the milling of sheet 12. They have upper walls provided by a lower surface 14a of the cover sheet 14.

The device 10 incorporates retro-reflecting mirrors 26 and 27 of high reflectivity copper. The mirror 26 has a stepped profile defining three
10 reflecting regions 26a, 26b, and 26c.

Radio frequency electrodes 29 are positioned above and below the beamsplitter waveguide 20 to couple energy capacitively into a gain medium within the waveguide.

15

The beamsplitter waveguide 20 is of rectangular cross-section, being of length L, width $2b$ and height $2a$ as indicated by scales 30. Here L, a, and b are parameters which may vary between different embodiments of the invention. In the device 10, $b = 6a$. The coupling waveguides 22 and 24
20 are of square section with side $2a$. The length L of the beamsplitter waveguide 20 is given by:-

$$L = 2nb^2/\lambda_o \qquad (1.1)$$

25

where λ_o is a free space operating wavelength of the device 10 and n is the refractive index of the medium within the beamsplitter waveguide 20. Alternatively, replacing n/λ_o by λ, the propagating wavelength in the
30 beamsplitter waveguide. Equation (1.1) becomes:

$$L = 2b^2/\lambda \qquad (1.2)$$

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In the device 10, $2b = 4$ mm, $2a = 0.67$ mm and $L = 0.755$ m for an operating wavelength λ of 10.59 μm. The sizes of $2b$ and $2a$ may be influenced by manufacturing tolerances associated with the milling process and the power requirements of the laser device.

5

The beamsplitter waveguide 20 has a central longitudinal axis 32 indicated by a dashed line. The axis 32 is a distance b from the side walls and a distance a from the lower wall of waveguide 20. The coupling waveguides 22 and 24 have respective central longitudinal axes 34 and 36,
10 which are parallel and coplanar with the axis 32. The axes 34 and 36 are located centrally of respective halves of the transverse cross-section of the beamsplitter waveguide 20, as indicated by the uppermost scale 30 in Figure 1.

15 For the purpose of analysis of the operation of the device 10, y and z Cartesian co-ordinate axes are shown at 38a and the x and y axes are shown at 38b. The z axis is parallel to the device's longitudinal axis 32. The x and y axes are transverse vertical and transverse horizontal respectively. The longitudinal axis 32 contains $x = 0$ and $y = 0$. The
20 value of z is zero in a plane where the coupling waveguides 22 and 24 merge with the beamsplitter waveguide 20 indicated by a chain line 40.

The device 10 is contained within a vacuum chamber (not shown) which is is evacuated and back-filled with a controlled amount of a CO_2 laser gas
25 of known composition. This gas acts as a gain medium within the beamsplitter waveguide 20. The vacuum chamber contains a window (not shown) which is transparent at the wavelength of the radiation produced by the device and which transmits radiation from the laser device. The vacuum chamber also contains electrical feedthroughs (not shown)
30 connecting the RF electrodes 29 to a power supply (not shown).

The theoretical propagation characteristics of a general rectangular waveguide will now be analysed. It is assumed that this waveguide has

height 2*a*, width 2*b* and is bounded by walls of a homogeneous dielectric material with complex dielectric constant. It is also assumed that these walls are highly reflecting, and do not attenuate propagating waveguide modes significantly. The waveguide has height, width and length

5 dimensions which are parallel to the x, y and z axes respectively. It has normalized linearly polarized modes of the kind EH_{mn}. The electric field contribution E_{mn} (x, y, z) of the mn^{th} mode EH_{mn} at the point (x, y, z) has been calculated by Laakmann *et al.* in Appl. Opt. Vol. 15, No. 5 May 1976, pages 1334-1340 as follows:-

10

$$E_{mn}(x,y,z) = \frac{1}{\sqrt{(ab)}} \begin{bmatrix} \cos \\ \sin \end{bmatrix}\left(\frac{m\pi x}{2a}\right) \begin{bmatrix} \cos \\ \sin \end{bmatrix}\left(\frac{n\pi y}{2b}\right) e^{i\gamma_{mn}z} \qquad (2)$$

15   where

m is the mode number relating to the field dependency along the x axis,

n is the mode number relating to the field dependency along the y axis,

20

z is the distance along the z axis,

$\gamma_{mn} = (\alpha_{mn} + i\beta_{mn})$, the propagation constant of the mn^{th} mode, β_{mn} and

25 α_{mn} being the mn^{th} mode's phase and attenuation coefficients, and

"cos" above "sin" indicates the former applies to odd mode numbers (m or n as appropriate) and the latter to even mode numbers.

30   To a good approximation, the phase coefficient β_{mn} is given by:-

$$\beta_{mn} = \frac{2\pi}{\lambda} \left[1 - \left\{ \left(\frac{\lambda m}{4a}\right)^2 + \left(\frac{\lambda n}{4b}\right)^2 \right\} \right]^{\frac{1}{2}} \qquad (3.1)$$

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If the negative term in parentheses in Equation (3.1) is small compared
with unity, that is if λ/a and λ/b are $\ll 1$, and m and n are low order
5 modes, which is satisfied in practice, then the binomial theorem may be
used to rewrite Equation (3.1) as:-

$$\beta_{mn} = \frac{2\pi}{\lambda} \left[1 - \frac{1}{2} \left\{ \left(\frac{\lambda m}{4a}\right)^2 + \left(\frac{\lambda n}{4b}\right)^2 \right\} \right] \qquad (3.2)$$

10

where a, b, m and n are as previously defined, and λ is the wavelength of
the radiation propagating in the waveguide.

15

Equation (2) sets out the electric field contributions obtainable from
all linearly polarised modes of a rectangular waveguide. It is
calculated on the basis that the electric field contribution of each mode
is zero at the side walls of the waveguide, i.e. at $y = \pm b$. This is
20 satisfied for a waveguide with reflecting walls. Not all rectangular
waveguide modes are necessarily excited by a given input. Any square
section waveguide which is selected to provide an input supplies an
excitation in the form of its fundamental or lowest order mode EH_{11}.
This is coupled to the various EH_{mn} modes of the rectangular section
25 waveguide. The input EH_{11} mode consequently becomes decomposed into a
linear combination of the EH_{mn} modes with respective complex
multiplication coefficients A_{mn}. This is expressed by:-

$$EH_{11} = \sum A_{mn} \cdot EH_{mn} \qquad (4)$$

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Essentially the A_{mn} amplitude coupling coefficients are the coefficients
of a Fourier series which represents the electric field at an input
aperture where the relevant input waveguide merges into the rectangular
waveguide. The EH_{mn} modes are mutually orthogonal, and in consequence
5 the coefficients A_{mn} can be calculated from overlap integrals of the
form:

$$A_{mn} = \int_{-b}^{+b} \int_{-a}^{+a} EH_{11} \cdot EH_{mn} \cdot dy.dx. \tag{5}$$

10

Referring now to Figure 4 there is shown a family of graphs, indicated
generally by 41, of electric field intensity I as a function of position
y, indicated by axes 42a, across a reference waveguide (not shown). The
15 reference waveguide is similar to the waveguide 20 except it has a length
of 2L. The reference waveguide has a cross-section identical to that of
the waveguide 20 as shown in Figure 3, with height $2a$ and width $2b$, and
has the same x, y and z axis orientations relative to the length, height
and width as the waveguide 20. The graphs of Figure 4 are calculated at
20 incremental values of z as shown by scale 42b. A square input waveguide
of side $2a$ (not shown), treated as operating in a fundamental mode,
provides an input 43 centred at $y = -b/2$ and bounded by $y = -b/2 \pm a$.
The input 43 provides for symmetric and anti-symmetric modes of the
reference waveguide to be excited.

25

The electric field intensities as a function of position at $z = L$ and
$z = 2L$ are indicated by lines 44 and 45 respectively. Line 44 shows that
at $z = L$ the electric field intensity has three maxima 46a, 46b and 46c.
These maxima have relative phase differences of $+13pi/8$, 0 and $+5pi/8$
30 radians respectively. At $z = 2L$, shown by line 45, the electric field
intensity has two maxima 48a and 48b centred on $y = \pm b/2$. At $y = +b/2$
the intensity maximum 48a has an intensity approximately 85% of input 43
and at $y = -b/2$ the intensity maximum 48b has an intensity approximately

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15% of input 43. The relative phases of the maxima 48a and 48b are pi
and 0 radians respectively.

Referring again to Figure 1, the beamsplitter waveguide 20 has a length L
5 equal to half that described above for the reference waveguide. The
mirror 26 which terminates the waveguide 20 has the effect of equating
the optical properties of the waveguide 20 to those of the reference
waveguide.   If the mirror 26 were to be replaced by a plane mirror
orthogonal to the axis 32, radiation originating from the reflection
10 coupling waveguide 24 would be split into radiation intensity maxima at
the mirror corresponding to the maxima 46a, 46b and 46c. These maxima
would be reflected and the radiation divided so that 85% of the radiation
intensity would be coupled to the output waveguide 22 and 15% would be
coupled back to the reflection waveguide 24. The mirror 26 has a stepped
15 profile.   The stepped profile of the mirror 26 has the effect of
introducing a relative phase shift in radiation reflected from the region
26a compared with that reflected from regions 26b and 26c because of a
difference in path length for radiation reflected from these regions.
The path length difference is equal to half a wavelength of radiation at
20 the operating wavelength. This path difference gives a relative phase
change between radiation reflected by region 26a and radiation reflected
by 26b and 26c of pi radians. With the stepped profile to the mirror 26,
85% of the radiation which is coupled to the coupling waveguides is
coupled to the reflection coupling waveguide and 15% of the radiation is
25 coupled to the output coupling waveguide.

The reflecting regions 26b and 26c of the mirror 26 are arranged so as to
reflect radiation corresponding to the maxima 46a and 46c respectively
The regions 26b and 26c are arranged so that the optical path length of
30 light reflected from these regions is $\lambda/2$ greater than that for radiation
reflected from the central region 26a.   The central region 26a
corresponds to the position of an intensity maximum equivalent to the
maximum 46b and has a width of 4a. The central region 26a protrudes from

the regions 26b and 26c by a length equal to $\lambda/4$ or 2.65 µm for a CO_2 laser device operating at 10.59 µm. The mirror 26 may be fabricated by a known 'lift-off' process as follows. A copper substrate is polished to give an optically flat and smooth surface. The regions 26b and 26c are

5 defined by an optical lithography process which leaves them coated with photoresist. Copper is then evaporated onto the substrate in a vacuum chamber so as to coat the region 26a and the photoresist with a thickness of 2.65 µm of high reflectivity metal. The photoresist is then dissolved using a suitable solvent. The metal evaporated onto the resist becomes

10 detached, leaving the region 26a standing proud of the regions 26b and 26c by 2.65 µm.

The operation of the laser device 10 will now be described. The vacuum chamber is pumped out and filled with a conventional CO_2 laser gas

15 mixture of $He/CO_2/N_2/Xe$ in the proportions 16:8:4:1 at a pressure of approximately 12 KPa which acts as the gain medium. An RF potential difference is than applied across the electrodes 29. This potential difference couples energy into the gain medium, raising the N_2 molecules to an energetic state which then transfer this energy to CO_2 molecules

20 through collisions. The power which is fed to the electrodes 29 will depend on the geometry of the device 10 and the required intensity of radiation; a worker skilled in the art of CO_2 lasers would determine the required power by experimentation.

25 Electromagnetic radiation is produced by the spontaneous relaxation of the energetic CO_2 molecules to a lower energy state. When this spontaneous relaxation produces a fundamental mode field entering the waveguide 20 from the waveguide 24, beamsplitting action occurs in a similar fashion to that shown in Figure 4. Approximately 15% of the

30 radiation, corresponding to the maximum 48b, is coupled to the output coupling waveguide 22 and emitted as an output beam along the axis 34 and the remaining 85%, corresponding to the maximum 48a, is coupled back to the reflection coupling waveguide 24 as a fundamental mode which passes

along the waveguide 24. During this "round trip" the intensity of the
radiation is increased by the stimulation of further molecular relaxation
processes.   The radiation passing along the waveguide 24 is reflected by
the   mirror 27 back along the waveguide 24 and back into the beamsplitter
5 waveguide 20, where the beamsplitting and amplification processes are
repeated.   The intensity of the radiation increases until, ignoring
losses, the rate of energy loss through the output coupling waveguide as
the   output beam is equal to the energy being pumped into the gain medium
by the RF electrodes 29. The mirror 27 may be adjustable so that it may
10 be   moved parallel to the axis 32. This movement changes the length of
the   reflection coupling waveguide 24 and enables the device 10 to be
tuned so that it forms a resonant cavity.

Referring now to Figure 5, there is shown a horizontal section plan view
15 of an embodiment of the invention configured as a sealed cavity laser
device indicated generally by 50. The device 50 has a base sheet 52
formed from a solid piece of alumina by milling to produce a beamsplitter
waveguide 54, a reflection coupling waveguide 56 and an output coupling
waveguide 58. The waveguides 54, 56 and 58 have identical dimensions to
20 the waveguides 20, 24 and 22 respectively. A cover sheet (not shown)
comprising a planar sheet of alumina is joined to the base sheet 52 to
form a gas tight seal between the sheets; this may be achieved by using
a process described in UK Patent number 2 141 655 B. A stepped mirror 60
similar to the mirror 26 and a plane mirror 62 similar to the mirror 27
25 are joined to the device 50 also to form a gas tight seal; this may be
achieved by a surface metallisation and brazing process or by gluing.
The   output coupling waveguide 58 has a gas pumping stem 64 attached to
one   end to form a gas tight seal with the device 50. Incorporated into
this pumping stem 64 is a window 66 transparent at the operating
30 wavelength of the device 50 and an output pipe 68 through which the
device 50 may be evacuated and the previously described CO_2 laser gas
mixture introduced. The window 66 may be a Brewster window, oriented at
an angle appropriate for transmission of radiation with an electric field

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component in the plane of the window. RF electrodes (not shown) are
arranged to excite the laser gas capacitively.

Figure 6 shows a horizontal sectional view of an embodiment of a laser
5 device of the invention indicated generally by 70 incorporating
electro-optic phase modulators. The device 70 incorporates a
beamsplitter waveguide 72, an output coupling waveguide 74 and a
reflection coupling waveguide 76 formed in a like manner to the
waveguides of the device 10. A retro-reflecting mirror 78 terminates the
10 waveguide 76. The device 70 also incorporates three modulation
waveguides 82a, 82b and 82c. The modulation waveguides 82a to 82c each
comprise a square section waveguide of side $2a$, and a retro-reflecting
mirror 84a to 84c. Whereas in the device 10, radiation is reflected by
the mirror 26 at an end of the waveguide 20 opposite the coupling
15 waveguides 22 and 24, in the device 70 radiation is coupled into the
three modulation waveguides 82a to 82c and reflected by the mirrors 84a
to 84c. Each modulation waveguide incorporates an electro-optic phase
modulator 86a to 86c whose optical path length is controlled by the
application of an electric field across it. By altering the optical path
20 length of each of the modulators 86a to 86c, the phase of the reflected
radiation coupled back into the beamsplitter waveguide 72 is controlled.

The electro-optic phase modulators 86 are of lithium niobate to which
electrodes (not shown) are attached. The phase modulators may be of
25 other electro-optic materials including ammonium dihydrogen phosphate,
potassium dihydrogen phosphate and barium titanate.

Alternatively, instead of incorporating a phase modulator 86 within the
modulation waveguides 82, the lengths of the modulation waveguides may
30 themselves be controlled. This may be achieved by mounting the mirrors
84 on piezo-electric manipulators (not shown). The lengths of the
modulation waveguides 82 are each controlled by the application of a
potential difference across each respective piezo-electric manipulator.

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Electronic control of the optical path lengths of the modulation waveguides 82 may be used to 'trim' the phase of radiation coupled from the modulation waveguides and so counteract dimensional changes of the
5 device 70 due to thermal expansion. In addition, the output intensity of the laser device 70 may be controlled by adjusting the optical path lengths of the modulation waveguides 82 so as to couple radiation less efficiently to the reflection coupling waveguide 76 and the output coupling waveguide 74. Alternatively, the electronic control may be used
10 to 'Q-switch' the device 70. In the Q-switching mode of operation, the the optical path lengths of the modulation waveguides 82 are deliberately set so as to prevent the device 70 acting as a laser. Electrical contacts (not shown) to the three phase modulators 86 are connected to earth so that there is no relative phase change between radiation coupled
15 from the three modulation waveguides. The device 70 is then in a "lossy" state and so a high density of metastable energetic CO_2 molecules is created. The phase modulators 86a and 86c in the waveguides 82a and 82c are then adjusted by the application of respective electric fields so that the relative phase changes are those which are required for lasing
20 action. The phase of the radiation coupled from the waveguides 82a and 82c are retarded by pi radians with respect to the phase of the radiation coupled from the waveguide 82b. Because of the high density of energetic molecules a burst of radiation is then emitted from the output coupling waveguide 74, which, if the respective electric fields across the phase
25 modulators are maintained, gradually decays to a steady state. If the electrical contacts to the phase modulators 86a and 86c are re-connected to earth when the device 70 starts to lase, 85% of the light within the device 70 is coupled to the output coupling waveguide 74 and the device undergoes a 'cavity dump', giving an intense burst of radiation whose
30 intensity quickly falls to near zero. This process may be repeated to give a pulsed output.

Referring now to Figures 7, 8, and 9, there is shown a further embodiment of the invention in the form of a solid state laser device indicated generally by 90. Figure 7 is a horizontal section and Figures 8 and 9 are vertical sections on lines VIII-VIII and IX-IX in Figure 7

5 respectively. The device 90 differs from previous embodiments in that it is constructed using solid waveguides. The device 90 is produced using standard semiconductor lithography techniques. The laser device 90 incorporates a substrate 92 of n-doped GaAs surmounted by a multi-layer waveguide structure 94. The waveguide structure 94 incorporates a

10 plurality of layers of the $Ga_{1-x}Al_xAs$ system surmounted by a metallization layer as shown at 95. A base layer 95a of n-doped $Al_{0.3}Ga_{0.7}As$ is covered by an active region 95b of $Al_{0.1}Ga_{0.9}As$ of thickness t which in turn is doped by layer 95c of p-doped $Al_{0.3}Ga_{0.7}As$. The three layers 95a to 95c form a pn junction. They are surmounted by a

15 layer 95d of p-doped GaAs and finally a metal layer 95e. Electrical connection to the device 90 is made via the metal layer 95e and a metal layer 95f on the base of the substrate 92.

Referring to Figure 7, the device 90 incorporates an output coupling

20 waveguide 96, a reflection coupling waveguide 98, a beamsplitter waveguide 100, and three modulation waveguides 101a to 101c. Radiation is generated and confined within the layer 95b; the layer 95b of Figure 9 thus forms the beamsplitter waveguide 100. The beamsplitter waveguide has a thickness t which is equivalent to the dimension $2a$ of the device

25 10. The coupling waveguides 96 and 98 and the modulation waveguides 101 have a layered structure similar to that shown in Figure 9 though without the metal layers. This layered structure provides waveguiding properties within a layer equivalent to layer 95b. The waveguides 96, 98, and 101 have a width equal to t. The beamsplitter waveguide 100 is of length L,

30 width $2b$, and height t. The length L obeys Equation (1.1), in which the refractive index n is equal to the value in the $Al_{0.1}Ga_{0.9}As$ region 95b and the free space wavelength λ_o of operation is 0.85 μm. The device 90 incorporates retro-reflecting end mirrors 102 and 104a to 104c attached

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to the waveguides 98 and 101a to 101c respectively. The output coupling waveguide 96 has an anti-reflective coating 108 applied to an end 110. The lengths of the individual modulation waveguides 101a to 101c are controlled during the lithography process to ensure the correct relative
5 phase modulation of radiation coupled into the beamsplitter waveguide as for the device 10. Thus waveguides 101a and 101c are $\lambda/4$ longer than waveguide 101b. Energy is coupled into the device 90 to raise electrons to an excited state by passing a current through the device.

10 Referring now to Figure 10, there is shown in horizontal section form a laser device of the invention, indicated generally by 120 and incorporating a symmetrical beamsplitting waveguide 122 fabricated in the same manner as device 10. The device 120 incorporates the beamsplitter waveguide 122, an output coupling waveguide 124, a reflection coupling
15 waveguide 126 fabricated in a similar manner to the device 10. The beamsplitter waveguide 122 has a length 2L where L is given by Equation (1.2), a width 2b and a height (not shown) of 2a. The coupling waveguides 124 and 126 are of square cross-section with sides 2a. The coupling waveguides 124 and 126 are positioned symmetrically on either
20 side of a central axis 127 and are spaced b apart. The device 120 also incorporates retro-reflecting mirrors 128 and 129. Radiation coupled from the reflection waveguide 126 is split into two maxima at the mirror 128, as indicated in Figure 4 by maxima 48a and 48b. The radiation is then reflected back towards the coupling waveguides 124 and 126. At the
25 coupling waveguides, the radiation is divided into two equal maxima. 50% of the radiation is coupled to the reflection coupling waveguide 126 and 50% is coupled to the output coupling waveguide 124. The device 120 does not require phase modulation of the radiation at the mirror 128 for its operation.

30
Figure 11 shows a Q-switched laser device of the invention indicated generally by 130. The device 130 incorporates an output coupling waveguide 132, a reflection coupling waveguide 134 terminated by a fully

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reflecting mirror 135, and a beamsplitter waveguide 136, fabricated in the same manner as the device 10. The beamsplitter waveguide 136 has a length 4L where L is given by Equation (1.2), a width 2b and a height 2a (not shown). The coupling waveguides 132 and 134 are positioned so that
5 they have a central axis 138a and 138b respectively, indicated by dotted lines, symmetrically offset from a central axis 139. The device 130 also incorporates two phase modulation waveguides 140a and 140b positioned so that they have central axes coaxial with axes 138a and 138b respectively. The phase modulation waveguides 140a and 140b are terminated by fully
10 reflecting mirrors 141a and 141b respectively. An electro-optic phase modulator 142 is incorporated into waveguide 140b. The phase modulator 142 is arranged to retard the relative phase of radiation reflected from the mirror 141b and coupled back into the beamsplitter waveguide 136 with respect to the phase of radiation coupled from the waveguide 140a by pi
15 radians on the application of a predetermined voltage across the phase modulator 142, which is termed the (pi) voltage. RF electrodes (not shown) above and below the device 130 capacitively couple energy into a gain medium within the waveguides 136, 132, 134, 140a and 140b. The waveguide 140a may be absent, in which case the mirror 141a is positioned
20 adjacent the beamsplitter waveguide 136, provided that the phase relationship between the radiation intensity maxima coupled back into the beamsplitter waveguide is maintained.

25 The device 130 operates as follows. The (pi) voltage is applied to the phase modulator 142, coupling all radiation from the reflection coupling waveguide 134 to the output coupling waveguide 132 thus creating a high loss cavity in which stimulated emission cannot occur efficiently. RF energy excites the gas molecules into an upper laser level. The phase
30 modulator 142 is then earthed allowing lasing action to occur within the device 130 but without coupling light to the waveguide 132 thus causing a rapid build up of the intracavity field. The (pi) voltage is then re-applied to the phase modulator 142, and all the radiation is then

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coupled to the waveguide 132 as a short intense pulse. The process is
then repeated giving a pulsed output. The intensity of the output pulse
may be adjusted by adjusting the voltage applied across the phase
modulator 142. If the voltage applied is not equal to the (pi) voltage,
5 a certain proportion of the radiation within the waveguide 136 is not
coupled to the output coupling waveguide 132 but is coupled to the
reflection coupling waveguide 134. The relationship between the output
intensity and applied voltage may be determined by routine systematic
measurement. The device 130 may be operated in a continuous output mode
10 as well as a pulsed output mode by controlling the voltage applied to the
phase modulator 142.

The beamsplitter waveguide 136 may alternatively have a length of 4L/3
with the coupling waveguides 132 and 134 and modulation waveguides 140
15 located at positions where y is equal to $\pm b/3$.

Figure 12 shows a further embodiment of the invention in the form of a
double output laser device, indicated generally by 150. The device 150
incorporates a beamsplitter waveguide 152 of width 2b, height 2a (not
20 shown) and length 2L with two reflection coupling waveguides 154 and 156
terminated by fully reflecting mirrors 158 and 160 respectively. The
device 150 also incorporates two output coupling waveguides 162 and 164
and RF electrodes (not shown) above and below the device to couple energy
capacitively into a gain medium. The waveguides 154, 156, 162, and 164
25 are of square cross-section with side 2a. The device 150 is effectively
two devices 10 joined end to end without the mirror 26. The waveguides
154 and 162 at a first end 166 of the beamsplitter waveguide 152 are
positioned at $y = +b/2$ and $y = -b/2$ respectively whilst the waveguides
156 and 164 at a second end 168 of the waveguide 152 are positioned at
30 $y = -b/2$ and $y = +b/2$ respectively.

In the device 150, radiation coupled from the waveguide 154 into the
waveguide 152 is amplified as it passes through the waveguide 152 and is

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divided into two intensity maxima at the second end 168. An intensity maximum of approximately 15% of the total radiation is coupled to the output coupling waveguide 164 and an intensity maximum of the remaining 85% is coupled to the reflection coupling waveguide 156 where it is
5 reflected and coupled back into the waveguide 152. The radiation coupled from the waveguide 156 passes back through the waveguide 152 and is again amplified and split into two maxima at the first end. Again 15% of the total radiation is coupled to the output coupling waveguide 162 and 85% is coupled to the reflection coupling waveguide 154 and the process
10 repeats itself. The device 150 thus has two output waveguides, and, in operation, once the device has reached a steady state, these two outputs are of equal magnitude with a constant phase relationship between them. In this configuration, the device 150 may be used to provide amplification of a signal emitted by the device and reflected of a
15 distant object back to the device.

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CLAIMS

1   A   laser device including waveguiding means (20) and first and   second
reflecting   means   (26,   27)   arranged   to   define   a   resonant   cavity,
characterised   in   that the waveguiding means (20) is arranged to   define
radiation   intensity   maxima   at   the first   reflecting   means   (26),   an
intensity   maximum   at least transiently at the second   reflecting   means
(27),   and   an intensity maximum at least transiently at a   first   output
(22) separate from the first and second reflecting means.

2   A   laser   device   according   to claim 1, characterised   in   that   the
waveguiding   means   comprises   a   multi-mode   waveguide   of   rectangular
cross-section (20, 54, 72, 100, 122, 136, 152).

3   A   laser device according to claim 2, characterised in that the   first
reflecting   means   includes   phase   shifting means (26a,   26b,   26c)   for
introducing a relative phase shift between the radiation intensity maxima
reflected by the first reflecting means (26).

4   A   laser device according to claim 3, characterised in that the   phase
shifting   means   comprises at least one subsidiary waveguide   (82a,   82b,
82c) arranged for propagation of radiation as a fundamental mode.

5   A laser device according to claim 4, characterised in that the said at
least   one   subsidiary waveguide is a plurality of subsidiary   waveguides
each   arranged   for   propagation of radiation as a fundamental   mode   and
terminated by respective reflecting means (84a, 84b, 84c).

6 A laser device according to claim 5, characterised in that the phase shifting means (86a, 86b, 86c) are electro-optic.

7 A laser device according to claim 5, characterised in that the respective reflecting means (84a, 84b, 84c) are adjustable in a direction parallel to a radiation propagation direction.

8 A laser device according to claim 7, characterised in that the respective reflecting means are mounted on respective piezo-electrically movable mounts.

9 A laser device according to claim 6, characterised in that the waveguiding means (72) and the first reflecting means (82, 84, 86) are arranged in conjunction to direct a radiation intensity maximum alternately between the second reflecting means (76, 78) and the first output (74).

10 A laser device according to claim 3, characterised in that the intensity of one of the radiation intensity maxima at the second reflecting means and at the output is of greater intensity than the other, and these two intensity maxima have an intensity ratio substantially equal to 85 to 15.

11 A laser device according to claim 10, characterised in that the intensity of the radiation intensity maximum at the second reflecting means is greater than the intensity at the output.

12 A laser device according to claim 10, characterised in that the waveguiding means and the first reflecting means are in conjunction arranged to direct the radiation intensity maximum of greater intensity alternately to the second reflecting means and to the output.

13 A laser device according claim 1, characterised in that the intensities of the radiation intensity maximum at the second reflecting means and the radiation intensity maximum at the output are substantially equal.

14 A laser device according to claim 1, characterisd in that the laser device has a second output separate from the first and second reflecting means.

15 A laser device according to claim 1, characterised in that the waveguiding means is a hollow waveguide.

16 A laser device according to claim 15, characterised in that the hollow waveguide has walls of alumina.

17 A laser device according to any of claim 1, characterised in that the waveguiding means is a solid waveguide.

18 A laser device according to claim 17, characterised in that the solid waveguide is of a semiconductor material system.

19 A laser device according to claim 18 wherein the semiconductor material system is $Al_xGa_{1-x}As$.
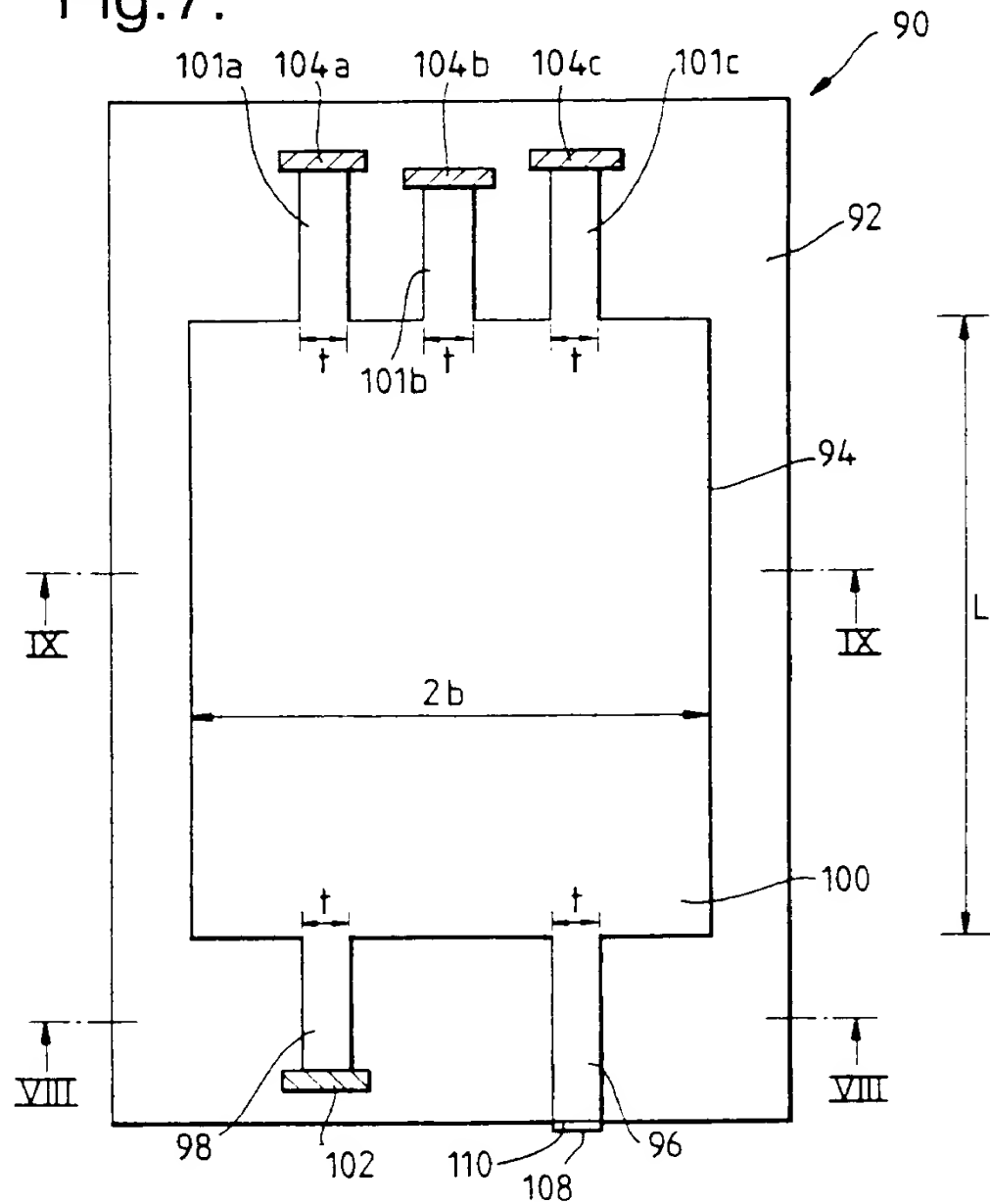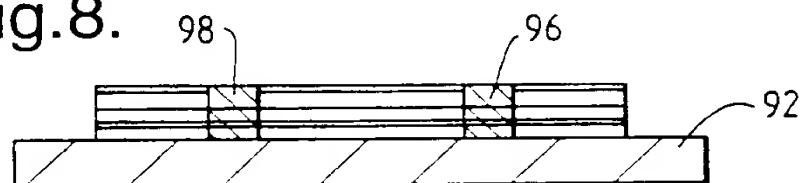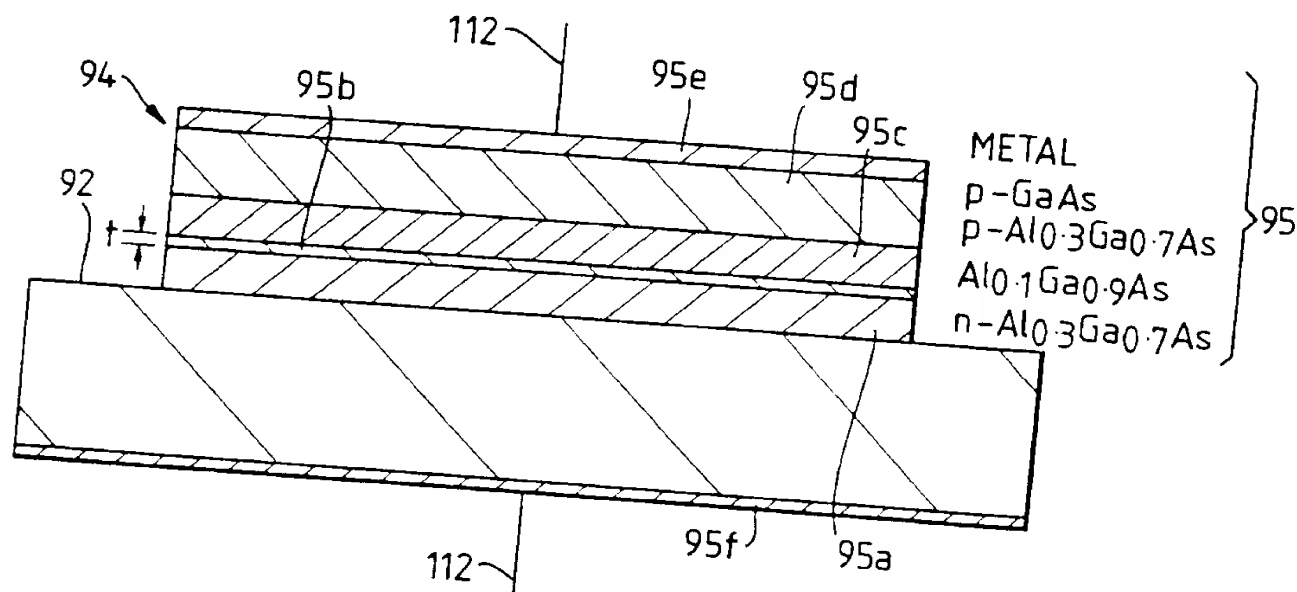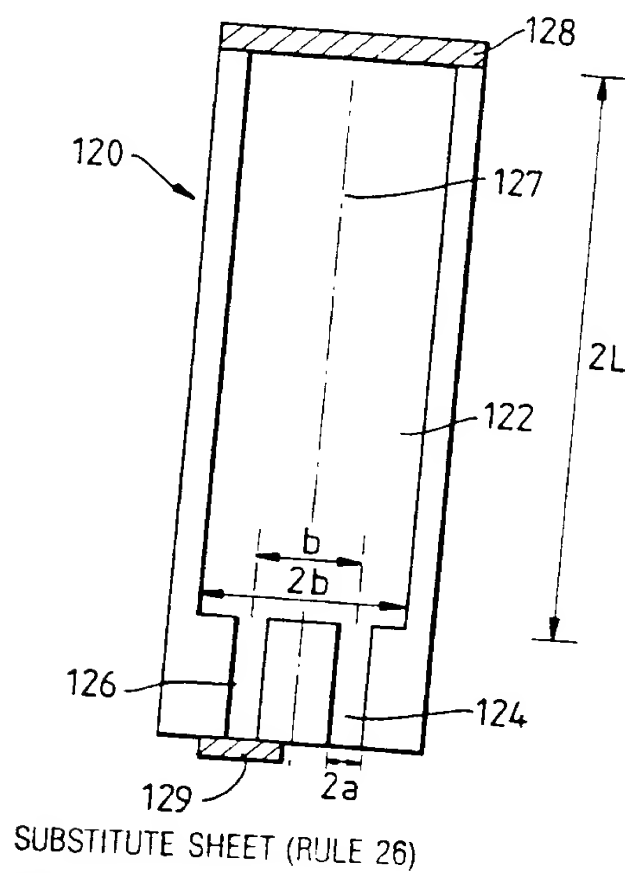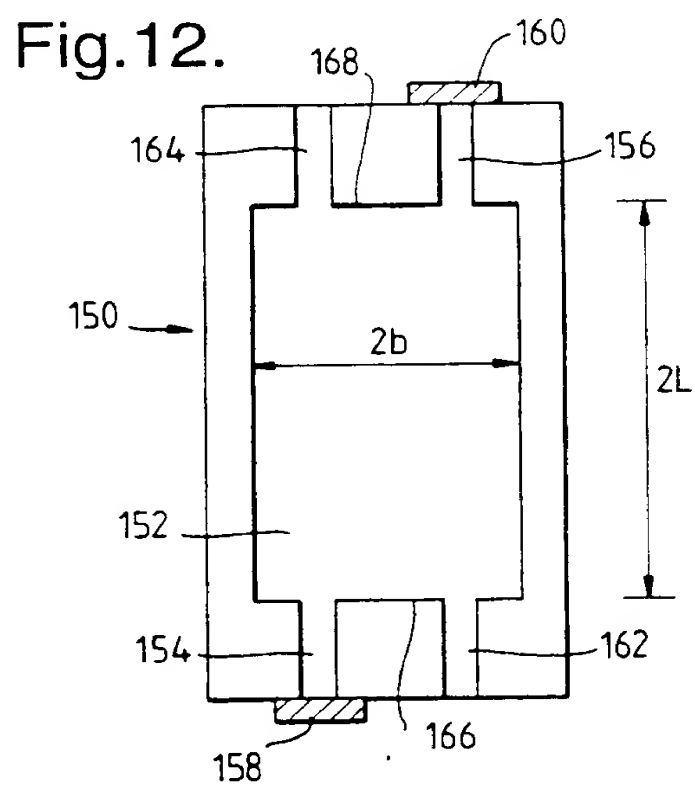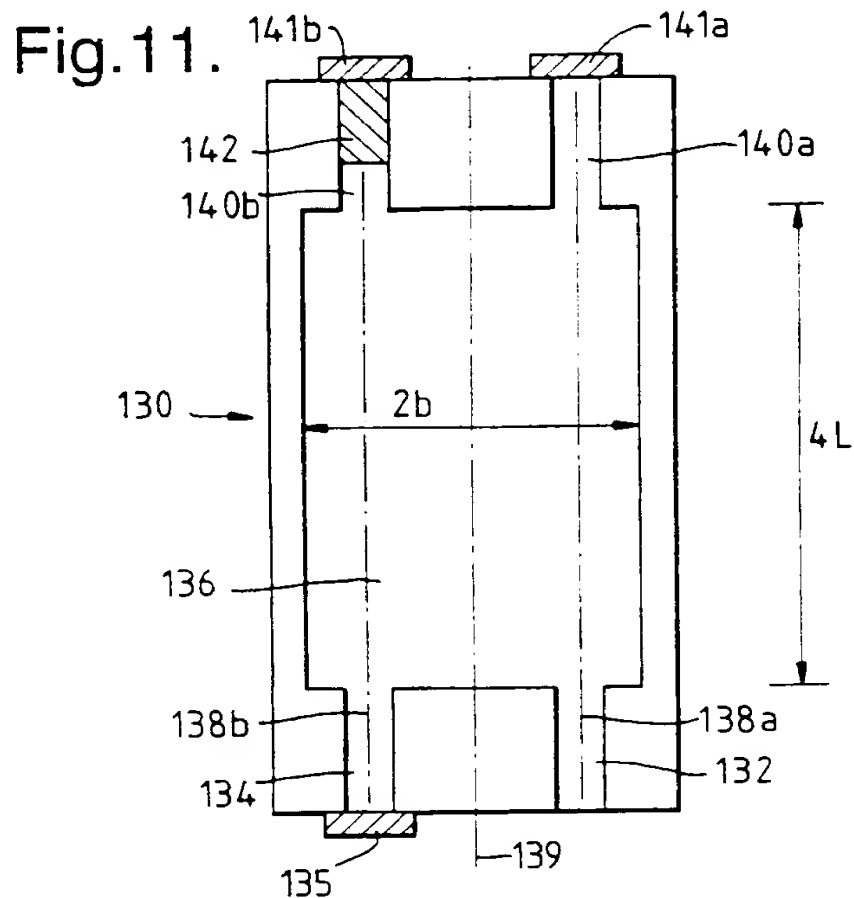
Fig.1.

Fig.2.

Fig.3.

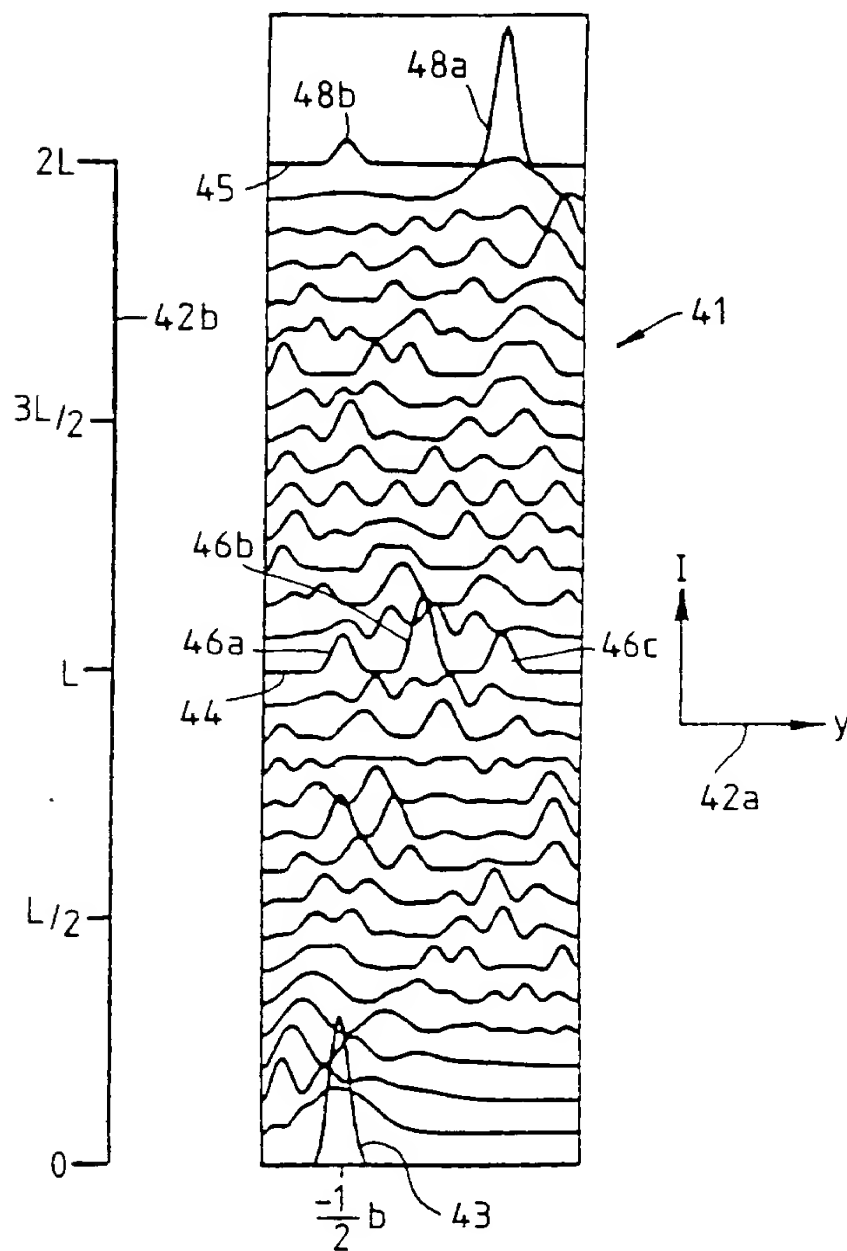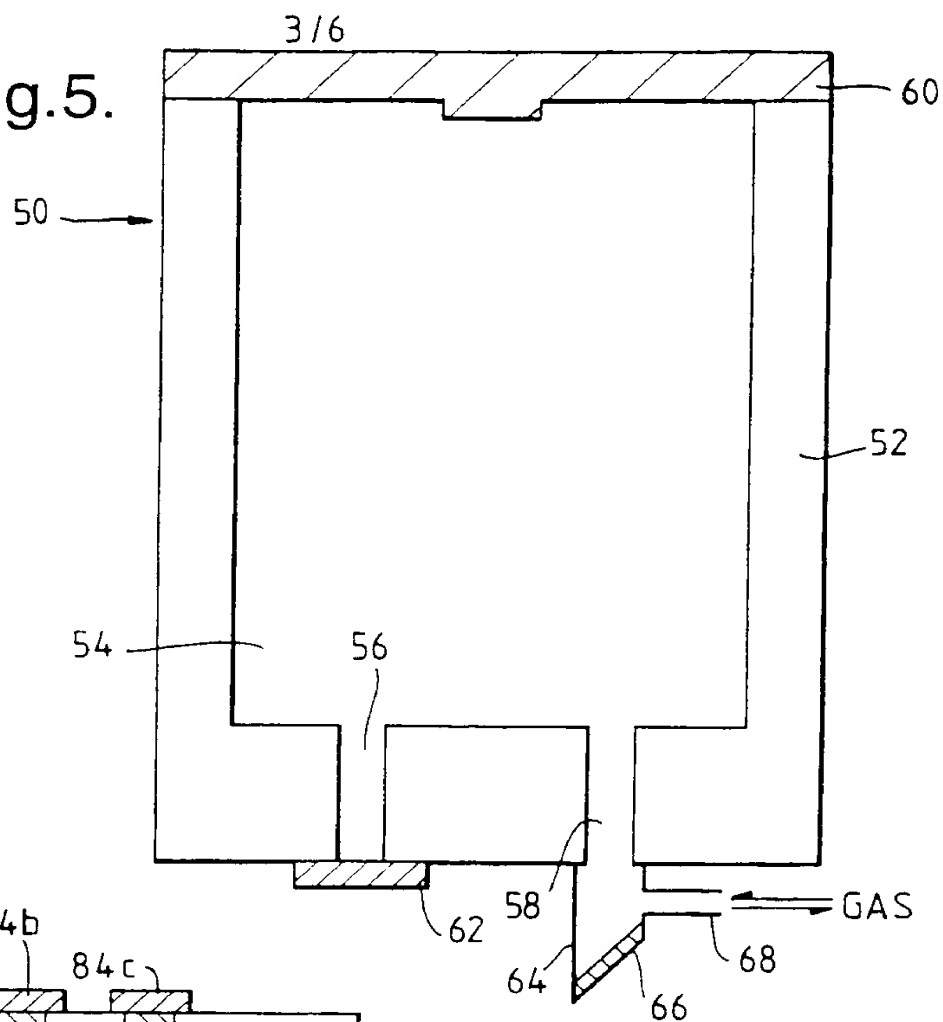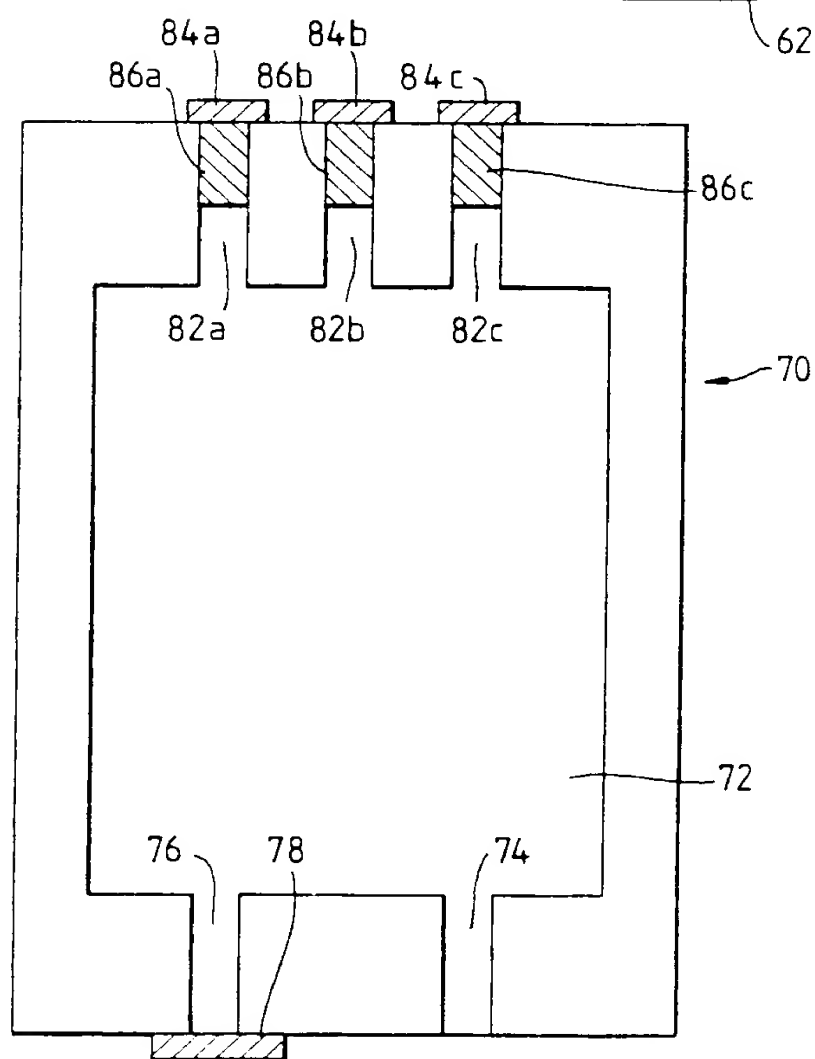# Fig.4.

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Fig.5.

Fig.6.

Fig.7.

Fig.8.

Fig.9.

METAL
p–GaAs
p–Al$_{0.3}$Ga$_{0.7}$As
Al$_{0.1}$Ga$_{0.9}$As
n–Al$_{0.3}$Ga$_{0.7}$As

Fig.10.

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Fig.11.

Fig.12.

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   H01S3/03   H01S3/25

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   H01S   H01C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO,A,92 11550 (THE SECRETARY OF STATE FOR DEFENCE IN HER BRITANNIC MAJESTY'S GOVERN.) 9 July 1992 cited in the application see page 38 - page 43; claims 1-11; figures 1-23	1,2, 14-19

[ ] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
1 August 1994	1 0. 08. 94

Name and mailing address of the ISA	Authorized officer
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/GB 94/01286

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
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		EP-A-	0563084	06-10-93
		JP-T-	6503902	28-04-94